

## Determination of the expected solar diurnal vectors of cosmic rays on the earth

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Received 20 November 2002, accepted 7 March 2003

**Abstract** : Using the best-fitting technique, we determined the parameters of the solar diurnal vector in free space by considering one space isotropy of the flat spectrum and by using the observed cosmic-ray data of the Deep River neutron monitor as well as the Socorro underground muon telescope over two solar cycles. Positive results have been obtained for these parameters. Further, we used the above parameters of the solar diurnal vector in free space to calculate the expected solar diurnal vectors of cosmic rays on the Earth for other 10 neutron monitor stations. Comparison between the observed and the expected solar diurnal vectors of the above stations shows that both the expected as well as the observed amplitude and phase are very close to each other for stations of low cut-off rigidity. However, as the cut-off rigidity increases, the expected and the observed amplitude and phase differ from each other.

**Keywords** Cosmic rays, solar modulation

ICS No. 96 40.Kk

### 1. Introduction

It has been of great interest to investigate the solar diurnal anisotropy of cosmic rays in free space. So far, many authors have studied the solar diurnal anisotropy in free space [1-12]. In all the previous analyses [1-12], the researchers analyzed the observed cosmic-ray data in order to study the rigidity dependence and its long-term modulation of the solar diurnal anisotropy of cosmic rays.

In this study, however, we are going to adopt another analysis. This analysis is mainly based on determining the parameters of the solar diurnal vector in free space by using pair cosmic-ray stations, and then using these parameters to calculate the expected diurnal vectors observed on Earth for other 10 neutron monitor stations. The comparison between the expected diurnal vectors and the observed ones can be considered as a measure of success of this analysis. This is an attempt to overcome the closing of cosmic ray stations, such as the closing of the well-known neutron monitor station of the Deep River at the end of 1990's.

### 2. The best-fitting technique

In order to examine the solar diurnal anisotropy in free space, we assumed that the diurnal anisotropy is uni-directional, having a flat spectrum (*i.e.* independent of energy), up to an upper cut-off rigidity  $R_{\max}$ , and amplitude ( $\alpha$ ) through direction ( $\theta$ ). The expected diurnal vectors observed on the Earth of every station

(i)  $[c_i^{\text{exp}} \& s_i^{\text{exp}}]$  can be represented according to Mori *et al* [10] in the following equations :

$$c_i^{\text{exp}} = \alpha a_i \cos(\theta - \phi_i), \quad (1)$$

$$s_i^{\text{exp}} = \alpha a_i \sin(\theta - \phi_i), \quad (2)$$

where  $a_i$  denotes the attenuation factor in amplitude, and  $\phi_i$  is the average deflection angle between the observed and the actual anisotropy vector.

To calculate the parameters characterizing the anisotropy, the components of the diurnal vectors were calculated according to eqs. (1) and (2). A matrix of vectors is assumed for every value of  $R_{\max}$ . The coupling coefficients used for the neutron

component are those derived by Yasue *et al* [13]; and the coupling coefficients of muon component are those derived by Fujimoto *et al* [14]. We re-derived these coupling coefficients for 46 values of rigidity instead of the 6 values derived by Yasue *et al* [13], and Fujimoto *et al* [14]. The method of this re-derivation has been discussed in our previous paper [7].

The best fitted values of the parameters were determined by the weighted least square fitting method, which is obtained by finding the deviation of calculated vectors  $[c_i^{\text{exp}} \& s_i^{\text{exp}}]$  from the observed ones  $[c_i^{\text{obs}} \& s_i^{\text{obs}}]$ , for each assumed set of parameters  $\sigma$  as shown below :

$$= \sum_{i=1}^n \left[ (c_i^{\text{exp}} - c_i^{\text{obs}})^2 + (s_i^{\text{exp}} - s_i^{\text{obs}})^2 \right] \quad (3)$$

### 3. Method of analysis

Firstly, we used the best-fitting technique in order to determine the components of the solar diurnal vector in free space. This was carried out by using the observed cosmic-ray data of the Deep River neutron monitor as well as the Socorro underground muon telescope over two solar cycles, and by considering one space anisotropy of the flat spectrum.

Secondly, which is our new analysis, we used the obtained parameters characterizing the solar diurnal anisotropy in free space [the upper cut-off rigidity ( $R_{\text{max}}$ ), amplitude ( $\alpha$ ) and phase ( $\theta$ )], to calculate the expected diurnal vectors observed on the Earth  $[c_i^{\text{exp}} \& s_i^{\text{exp}}]$  for another neutron monitor stations. These calculations were done by using eqs. (1 and 2), and by using the coupling coefficients derived by Yasue *et al* [13]. In these coupling coefficients[13], the attenuation factor in amplitude ( $a$ ), and the average deflection angle between the observed and the actual anisotropy vector ( $\Phi_i$ ) were derived. Finally, we compared the observed and the expected solar diurnal vectors of the above stations.

### 4. Experimental data

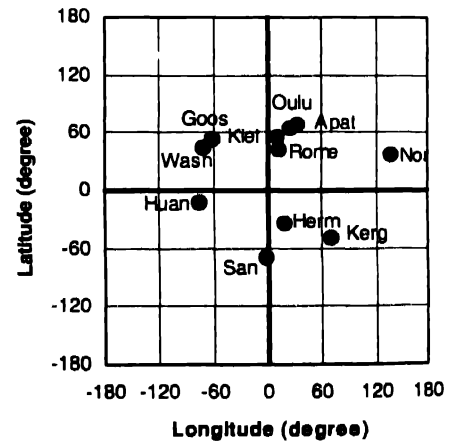
In the first half of this study, we calculated the parameters characterizing the solar diurnal anisotropy in free space by using the pair of stations: the Deep River (DR) neutron monitor as well as the Socorro (SOC) underground muon telescope over two solar cycles (20, 21) starting from 1968 up to 1988. We selected these two stations to follow Ahluwalia and Sabbah[15] in which they decided to use (DR) and (SOC) to calculate the spectral parameters of the anisotropy in free space. The median primary rigidities of response  $R_m$  of these stations cover the range of 16 GV  $< R_m < 331$  GV.

In the second half of this study; in which we calculated the expected diurnal vectors observed on the Earth, we used 10 neutron monitor stations. Table 1 shows the characteristics of

the neutron monitor stations used, while Figure 1 represents the distribution of these selected stations throughout the world. In this Table and Figure, we notice that these selected stations cover a wide range of latitudes, therefore cover the cut-off rigidities upto ~ 13 GV.

**Table 1.** The characteristics of the used neutron monitor stations

| No. | Station       | Geographic    |                | (GV) |
|-----|---------------|---------------|----------------|------|
|     |               | Lat. (degree) | Long. (degree) |      |
| 1   | Goose Bay     | 53.27         | -60.40         | 0.52 |
| 2   | Apatity       | 67.55         | 33.33          | 0.65 |
| 3   | Oulu          | 65.02         | 25.50          | 0.81 |
| 4   | Sanae         | -70.31        | -2.40          | 1.06 |
| 5   | Kerguelen     | -49.35        | 70.25          | 1.19 |
| 6   | Mt Washington | 44.27         | -71.30         | 1.24 |
| 7   | Kiel          | 54.34         | 10.12          | 2.29 |
| 8   | Hermanus      | -34.42        | 19.22          | 4.9  |
| 9   | Rome          | 41.90         | 12.52          | 6.37 |
| 10  | Huancayo      | -12.03        | -75.33         | 1.6  |



**Figure 1.** The distribution of the 10 selected stations throughout the world.

The data of neutron monitors are compiled by WDC whereas Prof. Swinson (private communication) provided amplitude of the diurnal variation of the Socorro underground muon telescope. This amplitude has been corrected for the Compton-Getting effect due to the Earth's orbital motion around the Sun.

### 5. Results and discussion

Figure 2 represents the year-to-year variation of the obtained parameters [ $R_{\text{max}}$ , amplitude ( $\alpha$ ) and phase ( $\theta$ )] of anisotropy. It is obvious from this figure that : (i) The amplitude of the solar diurnal anisotropy in space changes with solar activity, while the phase of the solar diurnal anisotropy in space have a tendency to change from ~18hr to ~15hr and then ~1

again with an approximate period of 22-year. This result has been discussed in our previous paper [6]. (ii) The upper limiting rigidity changes with the solar activity, in addition it has a relation with the nature of the heliosphere after a magnetic polarity reversal. This result was also discussed in one of our previous papers [7].

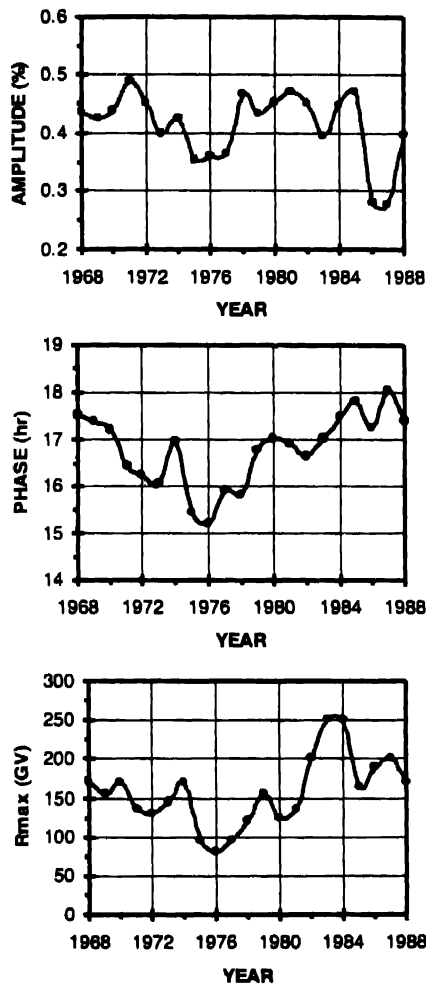


Figure 2. Year-to-year change in the parameters characterizing the solar diurnal anisotropy in free space; the amplitude (in the top graph), the phase (in the middle graph), and the upper limiting rigidity (in the lower graph)

Figures 3 and 4 compare the expected and observed solar diurnal amplitude and phase respectively for the 10 selected stations. It is obvious from these Figures that both the expected and the observed solar diurnal amplitudes of the 10 selected stations change with solar activity. Also, both the expected and the observed solar diurnal phase change somewhat within a 22-years variation. Further, It is clear that both the expected as well as the observed amplitude and phase are very close to each other for stations of low cut-off rigidity. However, as the cut-off rigidity increases, the expected as well as the observed amplitudes and phases separate from each other. We further calculated the average deviation of the calculated vectors from the observed ones for each of the selected 10 neutron monitor

stations by using eq. (3) after taking the square root. Figure 5 represents the relation between the cut-off rigidity of the selected 10 neutron monitor stations, and the average deviation for the period of study. We can conclude from this Figure that there is a direct relationship between this average deviation and the cut-off rigidity, in which the correlation coefficient is 0.8489961.

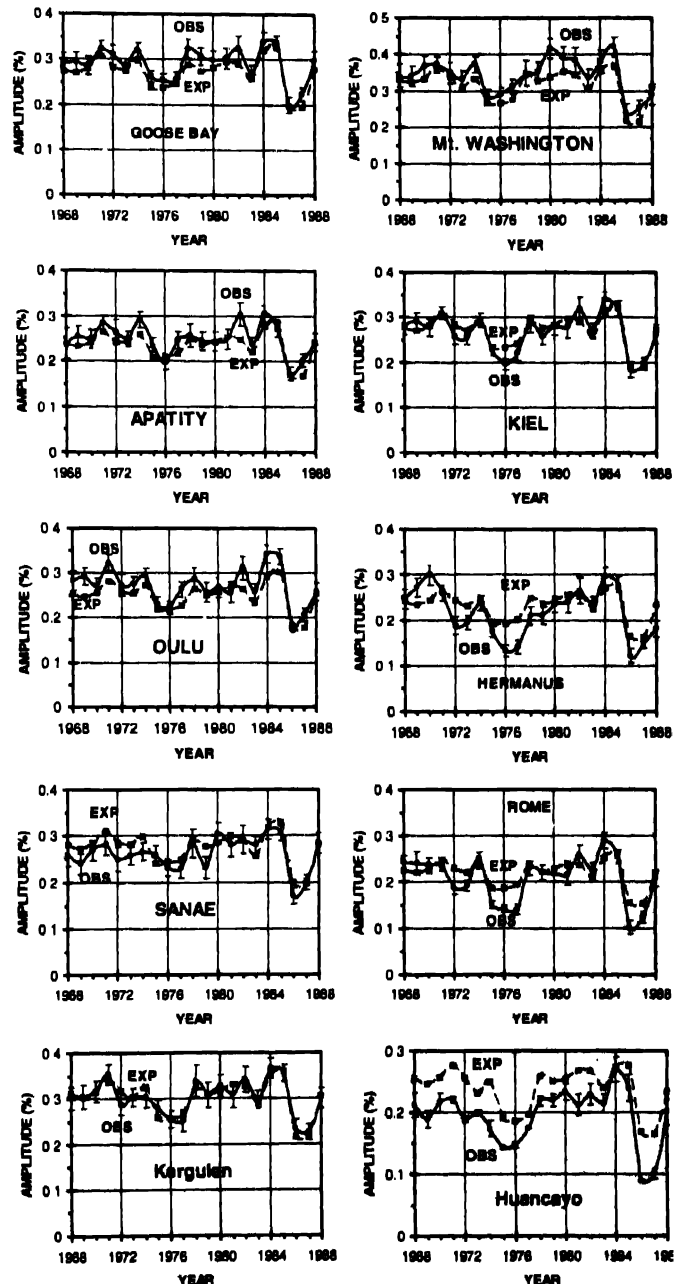


Figure 3. Comparison between the expected (dashed line with square mark), and the observed (solid line with circle mark) solar diurnal amplitude for the 10 neutron monitor stations.

We have probably succeeded in getting the expected solar diurnal vectors of the low-rigidity stations with little deviation from the observed diurnal vectors. While, as for the high-rigidity stations, we may need to re-consider some factors in determining the parameters characterizing the solar diurnal anisotropy in

free space. This is because the determination of the expected diurnal vectors depends on these parameters. One of these factors is the cosmic ray data used in the best-fitting technique, in which we used one neutron monitor station only (Deep River) along with one underground muon telescope only (Socorro). The other factor is the assumption of the diurnal anisotropy in free space, in which we considered one space anisotropy of the flat spectrum in this study.

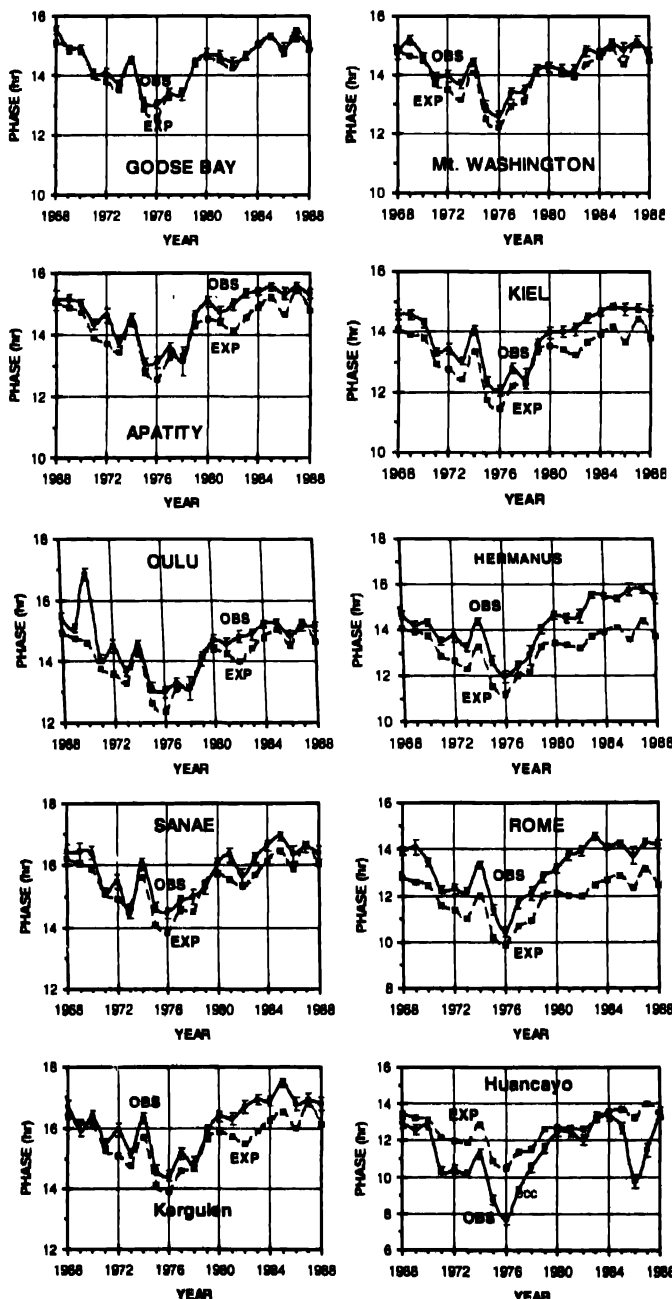


Figure 4. Same as Figure (3) but for the solar diurnal phase.

However up till now, there is no unambiguous conception on the origin of the secular changes of the cosmic rays anisotropy. Some authors associate it with the availability of more than one anisotropy source of different energy spectra

and different weight relationship[10-12]. However in most analyses[1-7] (like this one), it was revealed that the anisotropy is independent of energy with some upper cut-offs above which modulation vanishes. In other analyses [8, 9], it was revealed that the anisotropy had a power-type spectrum with the power exponent upto an upper limiting rigidity beyond which the anisotropy vanishes.

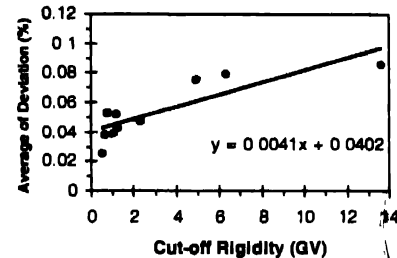


Figure 5. The relation between the cut-off rigidity of the considered 10 neutron monitor stations, and the average deviation between the observed and the expected vectors for the period of study

## 6. Conclusion

In this study, we determined the parameters of the solar diurnal vectors in free space by using the best-fitting technique. The study was carried out using cosmic ray data from the Deep River neutron monitor and the Socorro underground muon telescope over two solar cycles. On the one hand, we found that the amplitude of the solar diurnal anisotropy in space changes with solar activity, while the phase of solar diurnal anisotropy in space changes a little within a 22-years period. On the other hand, the upper limiting rigidity changes with solar activity, and has a relation with the nature of the heliosphere after a magnetic polarity reversal.

In addition, we used these obtained parameters of the solar diurnal vectors in free space to calculate the expected diurnal vectors observed on the Earth for another 10 neutron monitor stations. The comparison between the observed and the expected solar diurnal vectors of the above stations shows that both the expected as well as the observed amplitude and phase are very close to each other for stations of low cut-off rigidity. As the cut-off rigidity increases, the expected and the observed amplitude and phase separate from each other. We have probably succeeded in getting the expected solar diurnal vectors, with little deviation from the observed vectors of the low-rigidity stations. For the high-rigidity stations, some factors that were already discussed in this study, have to be re-considered.

## Acknowledgments

It gives me a great pleasure to thank Prof. D.B. Swinson for providing me with the Socorro diurnal amplitudes. Worldwide neutron monitors data are obtained through WDC-C2, to whom I owe much, I would also like to express my appreciation to Dr. S. Yasue for kindly introducing me to his coupling coefficients during the two years I spent in his department under the

supervision of Prof. S. Mori. Finally, I thank a lot to my supervisor Prof. A.A. Bishara for his kind help in revising this work.

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